SFR "Sodium cooled Fast Reactor"

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ABSTRACT

The objective of the paper being the discussion of the sodium technology related activities in Europe to highlight the link between the EURATOM projects defined in its Framework Programme and the GIF projects, the document is structured into four main parts.

After a short recall of the worldwide context - which is extremely favourable for the sodium technology - the SFR is shortly described within the context of the GenIV goals and the GIF governance.

The description of the planned SFR R&D programme allows situating the specific EURATOM role in the work on advanced fuels, with the contribution of the JRC-ITU on fuel fabrication.

The proposal for another EURATOM contribution is briefly presented, namely the Specific Targeted Research Project on Innovative Technologies for the Sodium cooled fast Reactor, which also points out the potential of other European organizations for the development of sodium technology.

A. INTRODUCTION

Nuclear energy has the potential to provide Europe with a secure and sustainable electricity supply at a competitive price and to make a significant contribution to the reduction of greenhouse gas emissions. The renew of interest for fast spectra to meet more ambitious sustainable development criteria (resources management and management of waste) and the deployment of an international shared R&D effort under the aegis of the Generation IV International Forum (GIF) [1], open a favourable framework for activities that have to allow developing innovative fission technologies.

Through several industrial realizations over the last tens of years, the sodium fast technology met the technical maturity without being able to achieve the economic competitiveness. Nevertheless, due to a new worldwide context, the Generation IV (GenIV) Sodium cooled Fast Reactor (SFR) system was identified during the GenIV Technology Roadmap preparation (http://gif.inel.gov/roadmap/) as a promising technology to perform in particular in the missions of sustainability, actinide management and electricity production, if enhanced economics for the system could be realized.

The main characteristics of the GenIV SFR that make it especially suitable for the missions identified in the Technology Roadmap are the following:

(1) High potential to operate with a high conversion fast spectrum core with the resulting benefits of increasing the utilization of fuel resources.

(2) Capability of efficient and nearly complete consumption of transuranics as fuel, thus reducing the actinide loadings in the high level waste with benefits in disposal requirements and potentially non-proliferation.

(3) High level of safety obtained with the implementation – among others - of inherent means that allow accommodation of transients and bounding events.

(4) Enhanced economics achieved with the use of high burn-up fuels, fuel cycle (e.g., disposal) benefits, reduction in power plant capital costs with the use of advanced materials and innovative design options, and lower operating costs achieved with improved operations and maintenance.

EURATOM, as a member of the GIF, has already elected to participate in the Sodium-cooled Fast Reactor (SFR) project with a consistent effort on advanced fuels. The Institute for TransUranium elements (ITU), an establishment of the Joint Research Centre of the European Commission, contributes to this project in collaboration with different GIF partners.

A second European commitment, the Specific Targeted REsearch Proposal (STREP, a tool of the EURATOM Framework Programme - FP) on Innovative Technologies for the Sodium cooled fast Reactor could, if it is accepted, open the SFR context to several European countries /organisations that are not yet members of the GenIV Initiative.

B. THE WORLDWIDE CONTEXT FOR THE SFR

With the European Fast Reactor (EFR) project the fast spectra sodium cooled systems reached a degree of optimization which was considered the asymptote for the pool integrated concepts with an oxide fuel and a Purex reprocessing. This project and the previous industrial plants in Europe and elsewhere (Phénix, Superphénix, etc.), confirmed the strong potential of the sodium cooled fast reactors both for the fissile creation and for the actinides transmutation.

As for the safety, the EFR project shows a level comparable to that of the best light water reactors with a very significant reduction of the probability of severe accidents and an effective capacity for the mitigation of the consequences.

In spite of this optimization the economic competitiveness was not reached and, with regard to the Gen III light water reactors, an additional cost of the order of 20 % on the capital cost and about 10 % on the cost of the kWh, was estimated.

Today, at international level, the recognized potential of the sodium cooled fast reactors justify studies and projects mainly in four different contexts:

(1) Within the GIF where the SFR studies (100 – 1500MWe) gather the efforts of six of the eleven partners of the GIF (South Korea, France, Japan, Euratom, UK, the USA);

(2) In Russia (Rosatom) where, leaning on the excellent functioning of BN600, the construction of the BN800 is restarting;

(3) In India with the construction of the PBFR (500MWe) which concretize the most important effort on the sodium technology;

(4) In China with the 25 MWe experimental reactor CEFR which start-up is foreseen in 2007, in the perspective of an industrial deployment of large sodium cooled reactors by 2020.

For the two latter countries, it is worth recalling their nuclear energy programs which, as indicated within the figure below, plan the deployment of more than 200GWe each by 2050, essentially based on fast spectra sodium technology.

C. The SFR and the GenIV Goals

Coherently with the GenIV Initiative, the GenIV SFR program [2] looks for ambitious long term goals on:

Sustainability goals and criteria: full utilisation of uranium resource and the recycling of actinides in a closed cycle. Furthermore, the minimisation of waste requires recycling both Pu and the minor actinides together in an integral homogeneous recycling of all actinides present in used fuel. There is also consensus in the project to minimise feedstock usage with a self-sustaining cycle, which only requires depleted or reprocessed U feed. This calls for a self-generating core with a breeding gain near zero.

Economics goals and criteria: Unit power will be considered in the range from >100 MWe (modularity) up to larger 1500 MWe size. GenIV objectives for construction time and costs, have to be considered.

Safety goals and criteria: aside the reduction of the operational effluents and wastes, the design objective is for no off-site radioactivity release even under accidental situation and it requires the efficiency, simplicity, robustness and reliability of safety related provisions (characteristics, systems and physical barriers).

Non-proliferation goals and criteria: the necessity to avoid, as far as possible, separated materials in the fuel cycle, implies minimising the use of fertile blankets. The objective of high burn-up together with actinides recycling results in spent fuel characteristics (isotopic composition) that are unattractive for handling. High burn-ups are the final objective.

D. Overview of the GenIV SFR R&D plan

To meet the goals above, the current GenIV SFR project is organized around two main design layouts: the loop type reactor and the pool type reactor. Two candidates are identified representing these two families: the Japanese Sodium Fast Reactor (JSFR - loop type) and the South Korean KALIMER (pool type). A specific activity to explore alternative options for components as well as for alternative layouts is planned with an objective to increase the competitiveness. The power level range for these concepts is defined as being 500 to 1500MWe. The consideration of a complementary track is underway, based on the preconceptual design for a Small Modular Fast Reactor (SMFR) provided jointly by the USA-ANL, CEA and JAEA, with a power level within the range of few hundreds of MWe.

Beside all these concepts, the European Fast Reactor (EFR) is recognized as being the basis to bring within the project the European background and expertise.

The important technology gaps for the SFR are in the areas of: capital cost reduction; ensuring of passive safe response to all design basis initiators, including anticipated transients without scram; proof by test of the ability of the reactor to accommodate of bounding events; scale-up of the pyroprocess with demonstration of high minor actinide recovery; development of oxide fuel fabrication technology with remote operation and maintenance. Some consider the acquisition of irradiation performance data for fuels fabricated with the new fuel cycle technologies to also be a viability issue, rather than a performance issue. Other important SFR reactor technology gaps are in-service inspection and repair (in sodium), and completion of the fuels database.

In small-medium size concepts (e.g. the SMFR), the key cost reduction is its modular construction and the implementation of fully new components which raise viability issues. The JSFR design implement innovations such as: a reduced number of primary loops; an integral pump and intermediate heat exchanger, and the use of improved materials of construction are the basis for cost reductions. The pool type Kalimer anticipates advantages in plant economy and safety through the utilization of the large thermal inertia. Totally passive safety mechanism is embodied in the concept for the Decay Heat Removal. The reduction of the number and/or elimination of safety classified equipment by design simplification and novelty, also contributes to the concepts' competitiveness.

With the advanced aqueous fuel cycle, the key viability issue is the minimal experience with production of ceramic pellets (using remotely operated and maintained equipment) that contain minor actinides and trace amounts of fission products. Further, it is important to demonstrate scale-up of the uranium crystallization step. Filling both of these gaps is essential to achieving cost goals. For the pyroprocess, despite the available knowledge, viability issues include lack of experience with larger-scale plutonium and minor actinide recoveries, minimal experience with drawdown equipment for actinide removal from electrorefiner salts before processing, and minimal experience with ion exchange systems for reducing ceramic waste volume.

The development of these concepts will be pursued following the guidelines indicated by the GenIV crosscut groups on economy, safety, proliferation resistance and physical protection. No premature down selection is mandatory before the end of the performance phase. The SFR activity will provide the follow on and the assessment of the promising systems evolution. The available conceptual designs will be evaluated versus an exhaustive set of criteria and indicators elaborated by the crosscut groups' indicators. Insights are expected from the GenIV Technology Roadmap and from the IAEA project INPRO.

The final selection for the SFR deployment will obviously rest with the industry and will likely result in a set of acceptable SFR systems.

To address the above issues, and to organize the corresponding activity, three Projects Management Boards (MB) are defining and will achieve the needed R&D under the responsibility of a SFR Steering Committee (SC):

(1) Design and Safety (& Integration) – D&S

a. Medium – high power level (500 to 1500MWe);

b. Low power level (100 MWe)

(2) Advanced Fuels (& Materials) - AF;

(3) Component design & Balance of Plant – CD&BOP.

Below the content and the objectives of the Design & Safety as well as the Component design & Balance of Plant projects are shortly discussed. A specific more detailed section is devoted to present the Advanced Fuel Project's content for the involvement of EURATOM bring an essential contribution.

D.1 Design and Safety (& Integration) – D&S [3]

According to the schedule currently defined by the SFR SC the milestones of the phases are specified and planned as follows: viability phase up to 2007, performance phase from 2008 to 2015, and demonstration phase for several years. In the viability phase, a design evaluation study and safety reviews of the design options will be conducted and most of the advanced technologies will be developed in this phase up to 2007.

Since extensive background knowledge and experience for SFR have already been accumulated, the period of the viability study phase for SFR is significantly shorter compared with other GenIV systems. Nevertheless, viability phase study for new options will be continued beyond the end of 2007. Example of these options still under assessment are the long-lived fission products (LLFP) transmutation and the advanced energy conversion systems (AECS) using supercritical CO_2 as working fluid.

At the end of the performance phase, the reference option will be selected from the conceptual design and safety assessment of design options.

In the area of Design, four R&D steps are progressively planned, namely, design evaluation study, conceptual design (basic design), conceptual design (detailed design), and design optimization. Figure 3a indicates the time schedule of design "design" activities. The design evaluation study will be conducted in the viability phase, and conceptual design will be in the performance phase. Each phase of the design study consists of a core design study, a system design study, and integration of the design. Therefore, a strong relationship should be maintained with the Advanced Fuel PMB and the Component Design and Balance of Plant PMB. As an option, a design study of a demonstration facility is considered and arranged in the design project.

In the area of Safety, two major roles are recognized: safety assessment of the designs in each design phase, and R&D to prepare the bases for the safety assessment. These activities should be performed coherently with the design activities; the time schedule of the safety project, is shown in Figure 3b. Development of the safety design requirements and a safety design review will be conducted in the viability phase, with a safety assessment in the performance phase. Associated R&D includes investigation of key phenomema in candidate fuel systems, development of analytical models, and development and confirmation of innovative safety related systems/components. In this area of safety a close working relationship will be maintained with the cross-cutting GenIV Risk and Safety Working Group

(RSWG) and the Proliferation Resistance & Physical Protection Working Group (PRPPWG). These cross-cut working groups will provide consistent and effective advice to each of the GenIV Systems.

A further Work Package, on "Reactor Operation and Technology Testing", is currently being defined: the initial tasks are focused on Phénix and Monju operation, and particularly the Phénix end of life tests and Monju start-up tests. Advanced technology testing tasks should be added later according to the SFR development needs.

The SFR demonstrator

As indicated above, the study for a demonstrator is presently under evaluation within the context of the D&S project, the objective being the demonstration of the retained SFR reactor options (SFR DEMO). The SFR DEMO has to be built with proven technologies but it must have a sufficient flexibility to achieve the demonstration that these selected options can be implemented and operated reliably and safely.

D.2 Component Design & Balance of Plant [4]

The viability of designing appropriate Component Design (CD) and BOP for SFR has been demonstrated with the design, construction and operation of previous SFRs. The main objective of this R&D project is related to system performance, either through the design of advanced components and technologies to enhance the economic competitiveness of the plant, or by researching the use of alternative energy transport systems in the BOP that could allow further cost improvements or expansion into new energy markets.

Component Design

The main area of R&D for component design is related to development of ISI&R technologies that can increase plant availability and lifetime. It is natural that the development of advanced components such as SGs is also of relevance in the R&D programme. This item is included in the advanced BOP development subsection below.

While not a viability issue, advanced ISI&R methods must be developed to enhance the performance of advanced SFR designs. Improvement of ISI&R technologies is important to confirm the integrity of safety related structures and boundaries that are submerged in sodium, and to repair them in place. Development of high quality sensors, remote-handling systems in sodium, and maintenance and repair equipment is necessary.

The main R&D elements for advanced ISI&R technologies include:

(1) Establishment of the Rules for fitness-for-service for SFR and an approach to inspection and assessment of structural integrity.

(2) Development of ISI&R technologies.

For sodium cooled plants, it is believed that sodium leakage monitoring by means of Non-Destructive Evaluation (NDE) has enough precision and reliability to detect the breach of the sodium coolant boundary.

Balance of Plant

The primary R&D activities related to the development of advanced BOP systems are intended to improve the capital and operating costs by means of advanced technologies. The main activities include (1) development of advanced, high reliability Steam Generators (SG) and (2) development of alternative energy transport systems based on Brayton cycles.

The primary purposes in the development of high reliability SG are to reduce the probability of a tube leak (causing a steam-sodium reaction) and to enhance the response time and reliability of detection systems if leakage in an SG tube occurs. The main R&D elements are:

(1) Minimization of SG tube leakage by design or by the use of advanced materials to reduce the probability of a tube leakage.

(2) Enhanced leak detection techniques, especially early detection systems to protect against small leaks and prevent the propagation of tube ruptures.

From the economic point of view, the use of an AECS with a Brayton cycle in the BOP offers the possibility of increasing the thermal efficiency of the plant and reducing the capital costs by replacing the usually larger components in a steam Rankine cycle. Supercritical CO_2 (SC-CO_2) has been identified as a candidate fluid because of the temperatures involved in the cycle and the potential compactness of the BOP equipment, the turbine in particular. R&D activities of interest include:

(1) Conceptual design study and assessments, including thermodynamic optimization for the SFR conditions, studies of the SC-CO_2 cycle components, conceptual designs for the sodium-to-CO_2 heat exchangers, and investigation of material implications.

(2) Study of technical performance and cost, including investigation of the safety implications of failure of the Na-CO_2 boundary, performance and cost evaluation.

(3) Planning for experiments to assess the behaviour of Na-CO_2 reactions and the performance of heat exchangers.

The figure 4 shows the main schedule for the two project parts.

D.3 **Advanced Fuels** [5]

The development of advanced fuel for the SFR includes advanced characteristics such as high burn-up and Minor Actinides (MA) bearing fuel to meet the GenIV goals, identified in the GIF Roadmap: 1) Potential to operate with a high conversion fast spectrum core for increasing resource utilization, 2) Capability of efficient and nearly complete consumption of transuranium elements as components of the fuel, 3) High level of safety obtained by the use of innovative and reliable solutions including passive safety measures, and 4) Enhanced economics achieved with the use of high burn-up fuels, fuel cycle (e.g. disposal) benefits, reduction in power plant capital costs and lower operation costs. In terms of high burn-up, current discussion suggests typical values of refuelling batch average burn-up of 150GWd/t for oxide fuel core [6] and 80GWd/t for metal fuel core.

Advanced fuels development efforts will consist of a primary evaluation, followed by the evaluation of the behaviour of MA fuels and of high burn-up fuels, concluded by a demonstration experiment with the selected advanced fuel. Oxide, metal (Uranium-

Transuranium-Zirconium type) and nitride fuels are the current advanced fuel candidates. Each step will contain tasks related to fuel performance and fabrication technology:

(1) Primary evaluation of advanced fuels (2007)

- (a) (U,Pu) fuel performance evaluation
- (b) MA bearing fuel performance preliminary evaluation
- (c) MA bearing fuel fabrication technology preliminary evaluation

(2) MA bearing fuels evaluation (2007-2010)

- (a) MA bearing fuel performance evaluation
- (b) MA bearing fuel fabrication technology evaluation

(3) High burn-up fuel behaviour evaluation (2011-2015)

- (a) High burn-up (U,Pu) fuel(s) performance evaluation
- (b) High burn-up MA bearing fuel(s) performance evaluation
- (c) Core materials for high burn-up fuel(s)

(4) Demonstration and application of advanced fuel (2016 and beyond)

- (a) Demonstration of advanced fuel performance
- (b) Demonstration of advanced fuel fabrication

Advanced fuel options will be defined at the end of 2007 based on the results of the primary evaluation. The evaluation of MA fuels will allow the primary selection of advanced fuels at the end of 2010: one or two promising fuels will be selected at that time. The final advanced fuel selection will be made at the end of 2015, for the start of the demonstration and application phase.

Primary evaluation of advanced fuels

Information of fuel performance and preliminary knowledge of MA bearing fuel performance and fabrication technologies should be prepared by the end of 2007. R&D issues related to fuel cycle technology are included in the consideration, like Low-DF (Decontamination Factor) oxide fuel and Advanced Dirty Oxide Fuel (ADOF). Experimental and analytical evaluation effort is required to prepare such information. The comparative studies among oxide, metal and nitride fuel should be performed to correctly define the "advanced fuel options" by the end of 2007.

<u>Oxide fuel performance evaluation</u>

Oxide fuel and sub-assembly concepts to satisfy both re-criticality issue from core safety viewpoint and core neutronic performance, such as breeding capability, are the most important issues [6]. As far as fuel pin concept is concerned, fuel smeared density and fuel form such as annular pellet and vi-pac are the typical specifications of interest. Experimental and analytical evaluation results to understand appropriate fuel smeared density and fuel behaviour up to high burn-up of 250GWd/t (point peak), which corresponds to 150GWd/t of average burn-up, are needed.

Irradiation tests of oxide fuel pins will be performed in PHENIX, JOYO and HFR. The CAPRIX in PHENIX should provide data on oxide annular fuel with 45%Pu at 10 at% burn-up. In JOYO, (U,Pu) oxide fuel (pellets) will be irradiated in parallel with MA bearing oxide fuel (see below). In HFR, (U,Pu) oxide fuel (sphere-pac) is irradiated in parallel with Np bearing fuel (see below). The results of JOYO and HFR tests will give data for fuel restructuring investigation.

Finally, the database of the dirty oxide fuel properties will be established for fuel performance evaluation

<u>Metal fuel performance evaluation</u>

The superiority in nuclear performance of a metal fuel core is due to the high number density of heavy metal nuclides in the fuel. Thermal conductivity, heat capacity, and transient axial expansion are also favourable characteristics. Although the countermeasure for the re-criticality issue is not evident in the current stage, it is classified as future issue for beyond 2007. The most important issue for metal fuel is fuel and cladding constituent inter-diffusion, which can lead to the effective thinning of the cladding and to liquid phase formation under certain high burn-up conditions. This issue is to be addressed by establishing a limit to the maximum cladding temperature. The current tentative limit is set to 650°C for cladding inner surface temperature, based on experience with U-Pu-Zr fuel clad in the ferritic-martensitic HT9 alloy. Experimental and analytical evaluation results to understand appropriate cladding maximum temperature up to high burn-up are needed as well as the information to evaluate the high burn-up capability of metal fuel.

Irradiation behaviour of metal fuel pins will be evaluated based on the available data and analytical calculation tools.

<u>Nitride fuel performance evaluation</u>

The better nuclear performance of the nitride fuel core is due, as for metal, to the high number density of heavy metal nuclides in the fuel. As for the metal fuel, thermal conductivity and heat capacity are also favourable characteristics. One of the most important issues of nitride fuel is its high burn-up capability. Nitride fuel pins have not been irradiated beyond 160GWd/t, and their life limiting feature seems to be the Fuel Cladding Mechanical Interaction (FCMI). The fuel pin specifications should allow a burn-up of 200-250GWd/t (pellet peak). Another crucial issue is identifying countermeasures to prevent re-criticality. There is also some concern of possible mechanical energy release due to severe Fuel Coolant Interaction (FCI) during core disruptive accidents. Experimental results and analytical evaluation are needed to understand these behaviours.

Irradiation tests and/or post irradiation examinations of nitride fuel pins irradiated in BOR-60 (BORA BORA experiment, up to 11-15 at% burn-up) and PHENIX (NIMPHE 1&2 experiments, up to 6.9 at% and 5.8 at% burn-up, respectively), will be performed by CEA and JRC-ITU to provide data on nitride fuel irradiation performance.

MA bearing fuel performance preliminary evaluation

MA bearing fuels will be used for the homogeneous recycling of transuranium elements, either from FR fuel reprocessing or from LWR spent fuel. The preliminary evaluation will be based on available information on the behaviour of these fuels under irradiation. For oxide fuels, data on MA fuel thermal performance, MA element redistribution and Fuel Cladding Chemical Interaction (FCCI) at high burn-up (over 5 at% for example) are of great importance. On the other hand, the absence of crucial issues associated with MA bearing metal and nitride fuels must be confirmed. An irradiation programme is underway to study of MA fuel performance and MA transmutation.

For SUPERFACT 1, a joint experiment of CEA and JRC-ITU, MA bearing oxide fuel pins had been irradiated in PHENIX up to 6.5 at% for low MA fuel and up to 4.1 to 4.6 at% for high MA fuel; MA transmutation rates had been measured. Further irradiation experiments are planned in JOYO (with oxide fuel pellets with 5%Am and 2%Am+2%Np) and HFR (with sphere-pac oxide fuel), which should provide data on MA redistribution and fuel restructuring. The database of the dirty oxide fuel properties will be completed for MA bearing fuel.

Irradiation tests of MA bearing metal fuel pins will be performed in the Advanced Test Reactor (ATR). In PHENIX, metal fuel with low MA+RE content is currently being irradiated (METAPHIX experiment [7], involving CRIEPI, JRC-ITU and CEA). Four types of alloy, namely, U-19Pu-10Zr, U-19Pu-10Zr-2MA-2RE, U-19Pu-10Zr-5MA and U-19Pu-10Zr-5MA-5RE, were fabricated by JRC-ITU and encapsulated for irradiation at different burn-ups. The capsule with low burn-up (2.4at%) was discharged from the core in August 2004, and non-destructive post irradiation started. The irradiated pins will be transported to JRC-ITU for destructive analysis. The transient behaviour of the metal fuel pins will be evaluated based on an analysis of the available data.

Irradiation tests of MA bearing nitride fuel pins are not planed in first step. An evaluation will be performed using analytical tools.

MA bearing fuel fabrication technology preliminary evaluation

The feasibility of MA bearing fuels fabrication, including the case of low decontaminated fuel, has to be evaluated. Experimental and conceptual study results are needed to evaluate technical issues such as MA bearing fuels fabrication parameters and remote fabrication system equipment.

MA bearing oxide fuel fabrication is being developed for the various irradiation experiments. For SUPERFACT 1, several batches of fuel, whose MA contents are 2%Np, 2%Am, 45%Np and 20%Np+20%Am, were fabricated. The obtained knowledge is useful for the preliminary evaluation. Laboratory tests of remote maintenance in fuel fabrication equipment will be performed, for screening of remote maintenance technology, resistance of process equipment and handling devices and demonstration under hot-cell environment.

Fabrication and characterization of MA bearing metallic and nitride fuels, including the fabrication of test fuel pins, out-of-pile testing and process optimization, will be performed in support of the irradiation experiments in ATR and PHENIX (FUTURIX FTA [8], see below).

MA bearing fuels evaluation

The next step will be the comparative studies among the "advanced fuel options" to allow a primary selection of "advanced fuel(s)" for SFR at the end of 2010.

MA bearing fuels performance evaluation

The thermal performance of MA fuels will be investigated through power-to-melt tests and the study of the high burn-up high temperature FCCI for oxide fuel, and of the high burn-up behaviour for metal and nitride fuels. Irradiation tests will be performed in PHENIX and JOYO.

The target of the FUTURIX FTA irradiation in PHENIX is the comparison of MA transmutation rates of different candidate fuels (oxide, metal, nitride and CERMET) under similar conditions. FUTURIX FTA irradiated in PHENIX is for high content of MA. The fuels are fabricated by CEA, US-DOE and JRC-ITU.

Furthermore, the metal fuel behaviour at middle and high burn-up (7at% and 11at%) will be studied with two other METAPHIX capsules (see above), which should to be discharged from PHENIX in 2006 and 2008, respectively, and sent to JRC-ITU.

In JOYO, oxide fuel pins with 5%Am and 2%Am+2%Np will be irradiated up to 10 at%. The tests should contribute to steady state behaviour studies of MA bearing fuel including FCCI. U-(Pu+MA)-Zr metal fuel pins will be irradiated, with a cladding inner surface temperature of 650°C, for the study of high temperature performance; data show a limitation of the liquid phase formation at low burn-up and FCCI at high burn-up

In addition, irradiation tests of ADOF will be conducted for performance modelling.

MA bearing fuel fabrication technology evaluation

The feasibility of mass production system should be evaluated by the conceptual study of commercial scale fabrication facilities.

MA bearing low-DF oxide fuel fabrication technology will be developed. Then again laboratory test of remote maintenance of fuel fabrication equipment will be conducted.

The ADOF fabrication process will be optimized, and the fabrication process in a demonstration scale will be established. The remote autonomous system for ADOF fabrication will be developed.

The process for the fabrication of MA bearing metallic fuels and fuel pins will be optimized. No specific plan related to MA bearing nitride fuel fabrication technology evaluation has been proposed yet.

High burn-up fuel behaviour evaluation

The studies of high burn-up capability of advanced fuel will lead to the final selection of the advanced fuel for the start of the demonstration and application step at the end of 2015.

High burn-up fuel(s) performance evaluation

Irradiation tests and transient tests of high burn-up fuel (oxide and metal) will be performed. The oxide fuel irradiation tests up to 250 GWd/t burn-up will be performed in JOYO, providing steady state behaviour data including FCMI and FCCI.

The irradiation tests of U-Pu-Zr metal fuel pins performed in JOYO will supply information on its high temperature performance, such as FCCI thickness at high burn-up. Then, transient tests of high burnup metal fuel pins will be conducted to evaluate the transient capability and behavior (This transient test is expected to be performed in the Transient REActor Test facility TREAT).

Transient tests of high burn-up oxide and metallic fuel pins will be conducted. (This transient test is expected to be performed in TREAT).

High burn-up MA bearing fuel(s) performance evaluation

Irradiation tests and transient tests of high burnup MA bearing fuel (oxide and metal) will be performed. The irradiation tests of MA bearing oxide fuel with low-DF of residual fission products (that corresponds to future fast reactor recycling) will be performed in JOYO, to investigate their steady state behaviour including FCMI, FCCI and MA redistribution up to 250 GWd/t of burn-up.

Transient tests of MA bearing oxide and metallic fuel pins should also be performed in TREAT. The transient behaviour of the fuels will be evaluated analytically.

Modelling and verification of ADOF performance are planned.

Core materials for high burn-up fuel(s) *[8]*

Oxide Dispersion Strengthened (ODS) ferritics and ferritic-martensitics are the reference core materials for fuel cladding tube and sub-assembly duct (wrapper tube). Irradiation tests of ODS ferritic(F/M) clad fuel will be performed in BOR-60 and JOYO. Scientific knowledge of ODS steel will be developed to promote advanced alloys for high temperature irradiation. This work is intended to produce the nano- and meso-scale structures required to ensure long term stability in a high temperature neutron irradiation environment.

Current irradiation tests in CEA about core materials, already achieved or in progress, including advanced austenitic materials (ex. MEMPHIS 3, OLIPHANT and PAVIX 8) are proposed.

Demonstration and application of advanced fuel

After the final selection of advanced fuel, demonstration and application activities become a major part of the SFR advanced fuel developmental activity. This includes demonstrations of MA bearing fuel performance and fabrication.

Demonstration of advanced fuel performance

Irradiation tests will be performed to demonstrate the prototypical GenIV SFR fuel sub-assembly integrity. The test subassembly specification will include reference MA bearing low decontamination fuel and reference core materials such as ODS cladding and ferritic-martensitic sub-assembly duct (wrapper tube).

Irradiation tests of MA bearing oxide fuel pins with low-DF of residual fission products (that corresponds to future fast reactor recycling) will be performed in JOYO, to study the steady state behaviour up to 250 GWd/t burn-up.

Demonstration of advanced fuel fabrication

Demonstration of MA bearing reference fuel fabrication will be performed by the fabrication of demonstration irradiation test fuel and sub-assemblies. The result should allow extrapolating the commercial mass-production facilities.

Figure 5 shows the time schedule for the Advanced Fuels project.

Global Actinide Cycle International Demonstration (GACID)

Recently, the new GACID project has been defined, a joint experiment of France, Japan and the USA, for the demonstration of MA burning in oxide fuel. Therefore, part of the tasks concerning advanced oxide fuels will be transferred to this new project.

Share of the work on advanced fuels

A first evaluation of the involvement of the different partners can be estimated from the present state of the planning, and is therefore affected by the maturity of the individual strategies. The main contributor is Japan, with defined inputs in every step of the project up to the long term, including irradiation experiments in JOYO. USA and France follow, participating at a similar level in all aspects of the projects (e.g. the irradiation experiments planned in PHENIX and TREAT), but only up to the MA fuel evaluation phase (and to the study of core materials for high burn-up). The contribution of UK and Korea are presently very low; KAERI withdrew its oxide related contribution, being more interested in the metallic option; new proposals are in preparation.

The EU participates in many of the on-going and planned experiments (SUPERFACT, METAPHIX, FUTURIX, NIMPHE), in collaboration with the Japanese, French and US partners. Its contribution consists of either a direct involvement of ITU in the fabrication of fuels and their post-irradiation examination, or a support from the FP indirect actions (EUROTRANS for FUTURIX, see also ITSR below). EU is therefore today a medium-size contributor to the project, but with the possibility of offering more support, especially for the later stages.

Link with the fuel cycle issues

The selection of the best advanced fuel candidate for the SFR will be based on the results of the studies described in the Advanced Fuels Project, but also on considerations concerning the fuel cycle. One of the goals of the program is the recycling of the actinides in a closed cycle, and different options are proposed for the reprocessing of the spent fuel. The selected fuel will first have to be suited for the chosen technique, and its composition will depend on the partitioning performances of this technique.

Studies are underway at ITU on the SUPERFACT 1 fuel, to evaluate the feasibility and the performance of the different reprocessing options. On the other hand, the METAPHIX experiment is expected to help determining the maximum acceptable lanthanide content in the fuel with regard to the fuel/cladding interaction, and this will have to be confronted with the separation factor of the reprocessing step. Furthermore, the amount of curium present is the fuel is an important element for the evaluation of the fabrication technologies.

E. THE GIF GOVERNANCE AND THE LINKS WITH THE SFR

The general GIF governance is recalled in Figure 6; the three levels of agreement / arrangements are indicated. The management structure for the SFR project is showed on figure 7. The GIF Framework Agreement has been signed by six partners since February 2005. For the SFR, the System Arrangement is almost finalized and will be likely signed by the mid 2006. The negotiation for the SFR Projects Arrangements is starting; their signature is expected for the year 2006.

The figure 7 also shows the links with the GIF governance entities. These links concern in particular the Expert Group (EG) and the so called "crosscut groups" on Economy (Economic Modelling Working Group – EMWG), Safety and reliability (Risk & Safety Working Group - RSWG) and Proliferation resistance & Physical protection (PR&PP). These groups feed the projects with insights in terms of approaches for the system design and on methodologies for their assessment.

These systematic interactions between the crosscut groups and the systems SC and MB allow guaranteeing the whole coherency for the design and the assessment of the different GenIV systems.

F. THE STREP ON INNOVATIVE TECHNOLOGIES FOR SODIUM COOLED FAST REACTOR: OBJECTIVES & STRUCTURE

Through the systematic search for innovations, the Innovative Technologies for the Sodium cooled fast Reactor (ITSR) FP6 project is mostly directed at the sodium technology competitiveness that is one of the most ambitious goals of the GenIV SFR R&D Project performed under the aegis of the GIF. Improvements on Safety; Environment; Waste management (through transmutation of the minor actinides); Proliferation resistance & Physical protection have also to be considered as essential complementary goals for the future SFR and are pursued with the ITSR project.

The project strategy and content takes full advantage of all the past expertise available in Europe and worldwide; strong synergy is implemented and kept with the GenIV SFR project. The objective being the identification of innovative technology options, the project is structured into five main technical work packages (WPs):

(1) Reactor and core design,

(2) Safety assessment

(3) Fuel with Minor Actinides,

(4) Concept and circuit technology; fuel handling,

(5) Advanced energy conversion system.

A Coordination & Integration WP will insure the whole coherency of the project and will provide the assessment vis-à-vis of the GenIV goals. Figure 8 shows the whole suggested structure for the projects' management.

During its 3 year period (2006 – 2009) the ITSR project, in close relationship with the currently under definition GenIV SFR project, will bring a European perspective to the GenIV SFR project identifying, suggesting and motivating innovations that can help meeting the SFR goals. This input will contribute mainly on the following items:

(1) The pre-selection of SFR reference design options and promising alternatives;

(2) The safety approach for SFR;

(3) The identification of the R&D needs for SFR;

(4) The selection of the SFR Demonstrator options and the definition of its missions.

This ITSR project is directed towards the specific objectives topics requested in the European Commission call "to assess the critical scientific issues and the technical feasibility of fourth generation reactor systems and fuel cycles".

As discussed above EURATOM, as a member of the GIF, has already elected to participate in the SFR project and especially within the Advanced Fuels project. The ITSR project complements this participation. It represents a unique opportunity to bring together countries experienced in sodium technology (Commissariat à l'Energie Atomique, France; CESI, Italy; Cranfield University, UK; Empresarios Agroupados, Spain; Electricité de France, France; Energovyzkum, Czech Rep.; Framatome ANP, France; Forschugszentrum Karlsuhe, Germany; Joint Research Center, Europe; Nuclear Research and Consultancy Group, Netherlands; Nuclear Research Institute Rez plc, Czech Rep.; NEXIA Solutions, UK; NNC, UK). It will be essential for GenIV to benefit from the extensive experience in the sodium technology, acquired over the years by European countries. Some of these countries never stopped working on this technology, designing or operating plants. Others want to renew their competences engaging young engineers; the latter will be formed to the whole nuclear system design. The view brought by these young engineers is a tremendous asset to meet the ITSR SREP goal for the identification and the assessment of innovations which can allow achieving the SFR competitiveness while guaranteeing the meeting of the other GenIV goals.

The Gas Cooled Fast Reactor (GCFR) STREP is also a EURATOM FP6 project, dealing with the development of the Gas Fast Reactor system. Both projects are complementary: parts of the studies covered by the GCFR are of a "cross-cutting" nature, i.e. some results will be of relevance for the SFR system too.

G. CONCLUSIONS

The GIF Roadmap is a worldwide effort to develop the nuclear reactors of the future, with the goal of optimizing the exploitation of fissile materials under the best conditions of safety and security. Europe had to participate in this effort, because it needs to be knowledgeable and experienced in this development, for its proper safety, sustainability and economical acceptability studies. While France and the UK are full members of GIF, the Member States of the EU may be involved through the EURATOM membership.

The JRC participate in many projects, either representing EURATOM in co-ordinating the European contribution, or directly as a research organisation interested in this R&D initiative with the best world-wide laboratories in the domain. For the SFR system, JRC-ITU is already contributing to the programme on advanced fuel, mainly in the fabrication for MA bearing fuel performance; participation in the further steps of the programme is probable and under discussion. Another important EURATOM contribution is proposed with the ITSR project.

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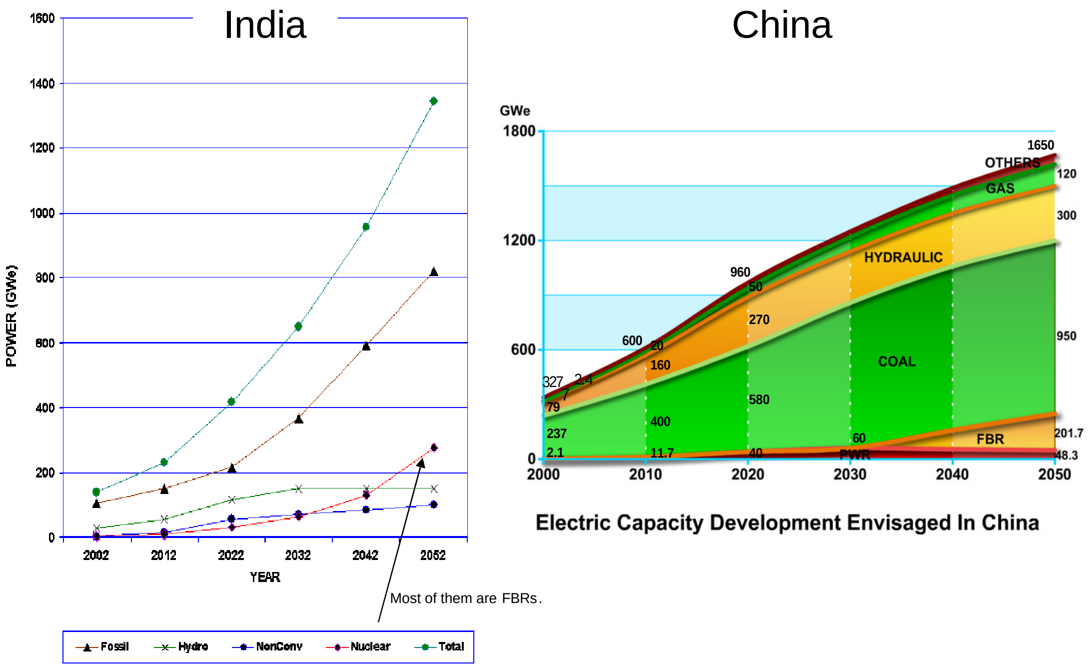

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Figure1. Plan for the energy sources deployment in India and in China

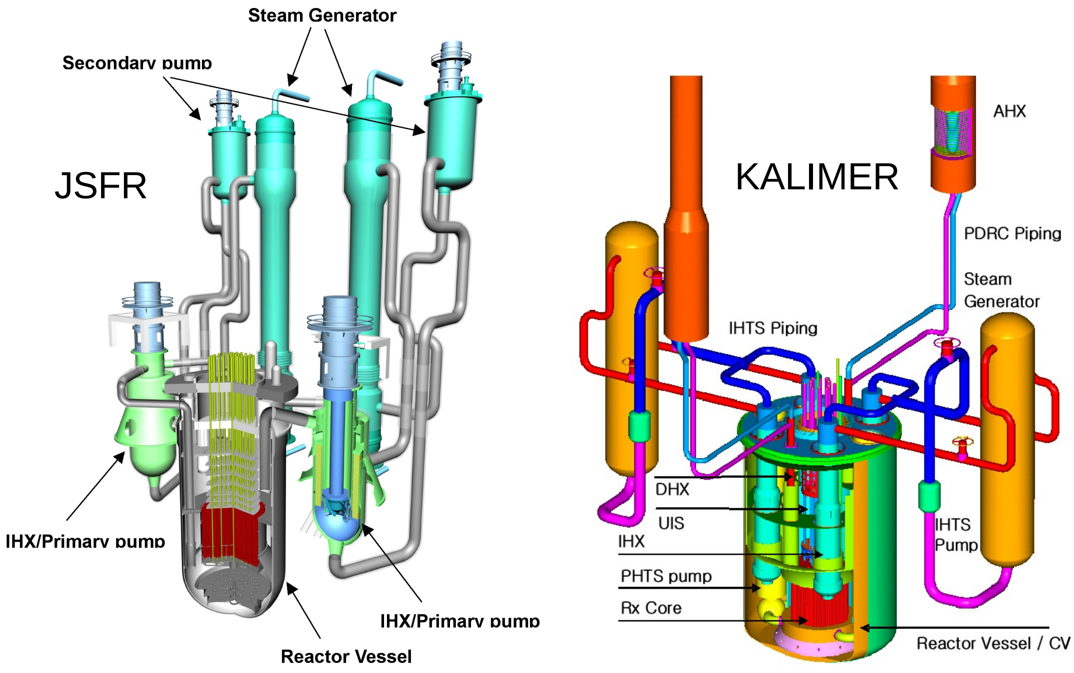

Figure 2. JSFR and KALIMER layouts and main characteristics

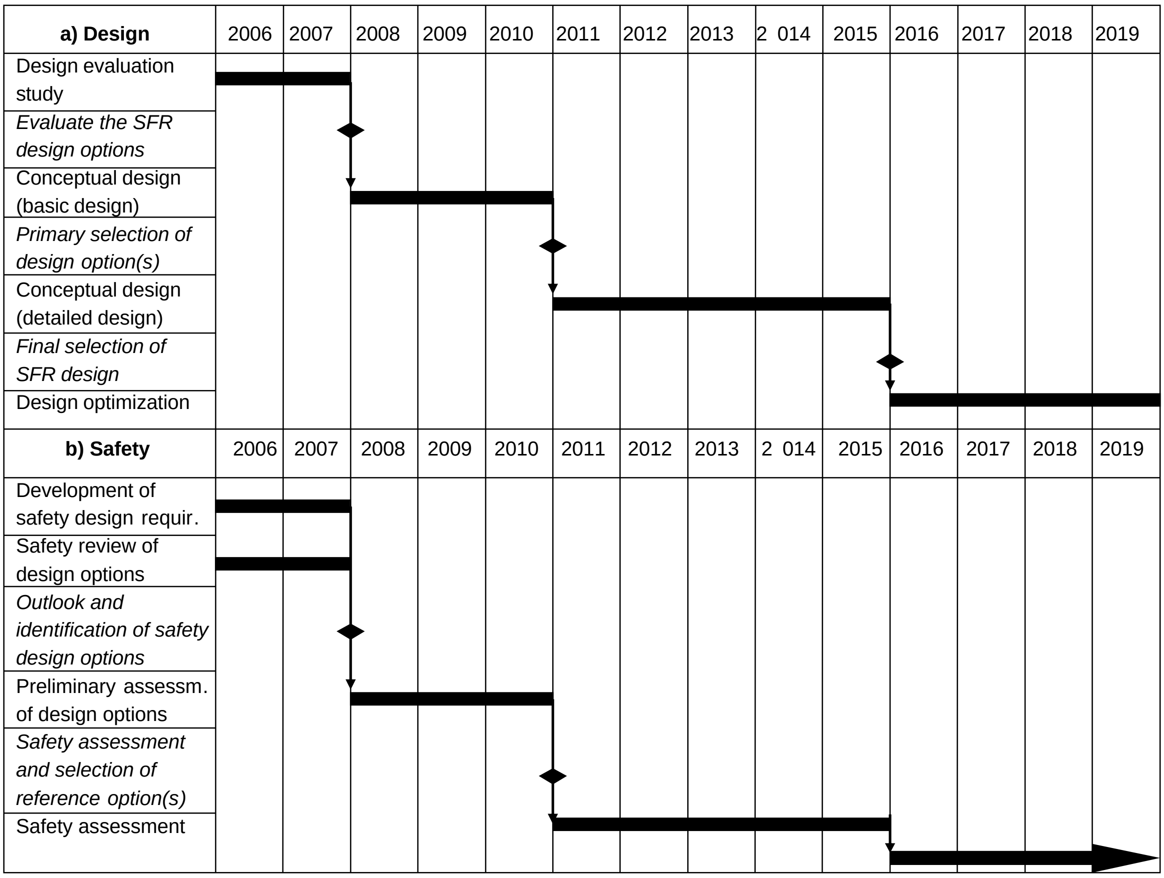

Figure 3. Time Schedule of the "Design & Safety" project

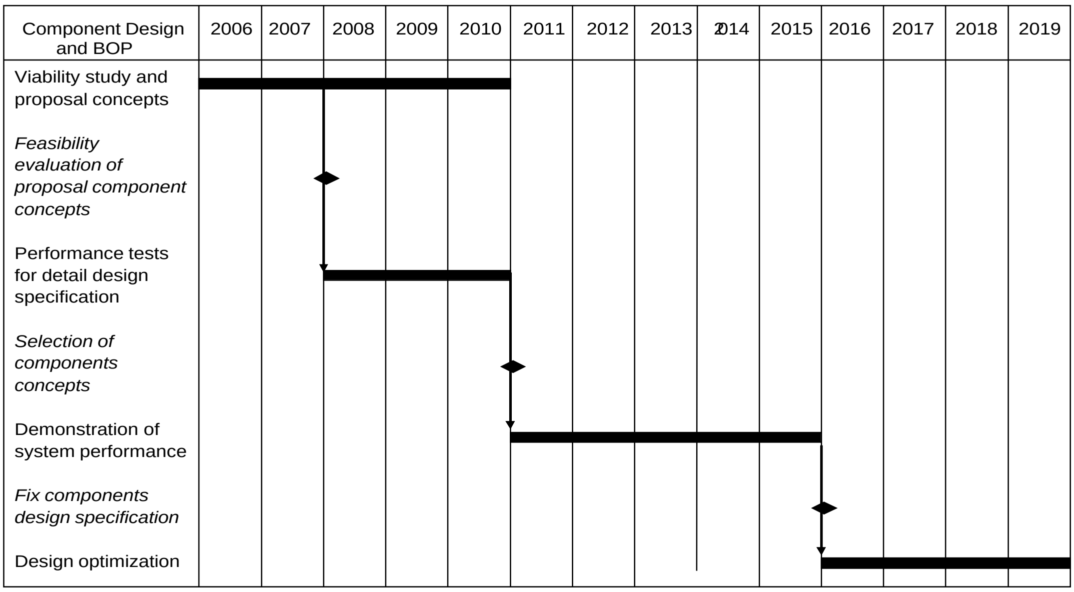

Figure 4. Time schedule of the "Component Design & BOP" project

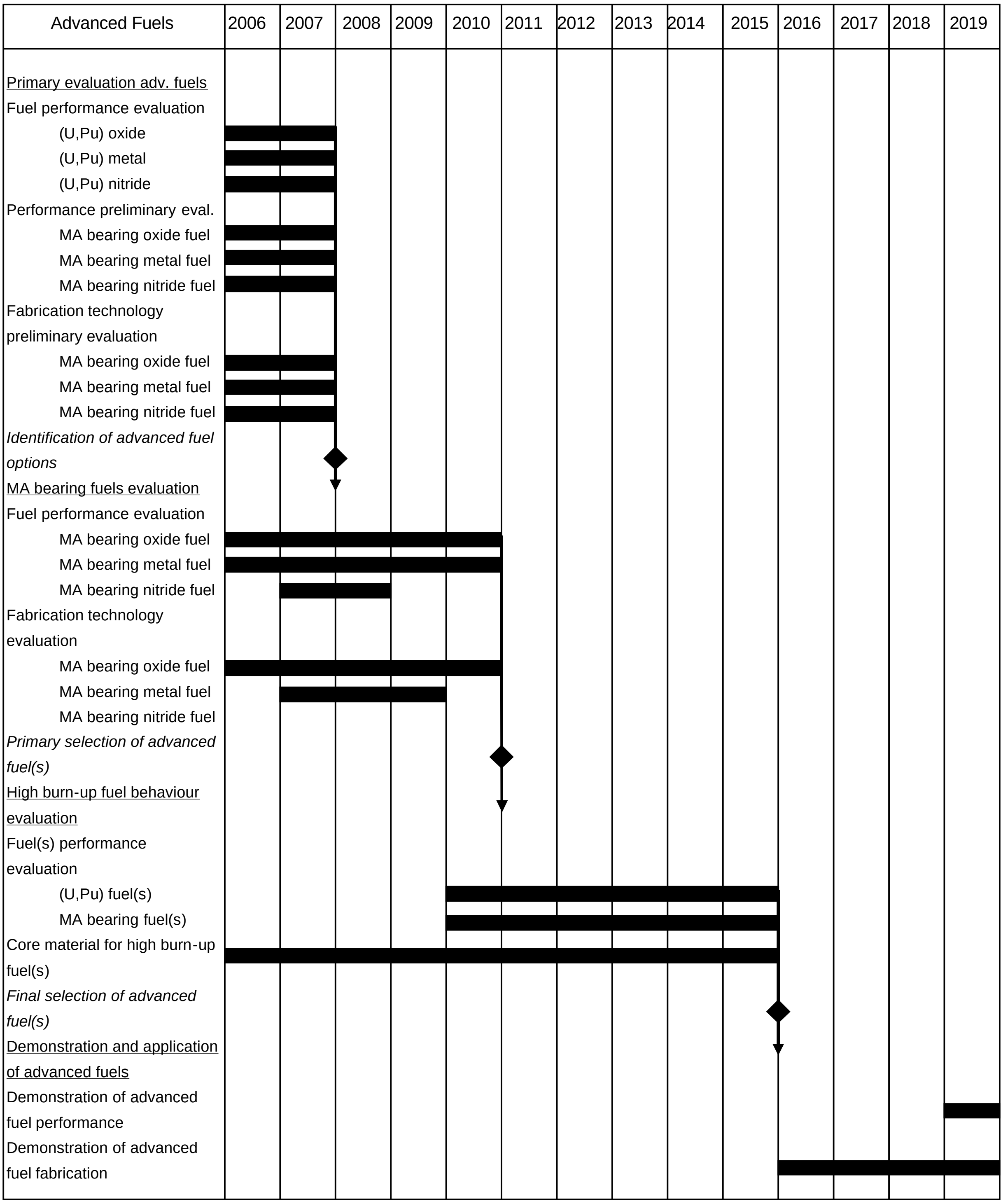

Figure 5. Time schedule of the “Advanced Fuels” project

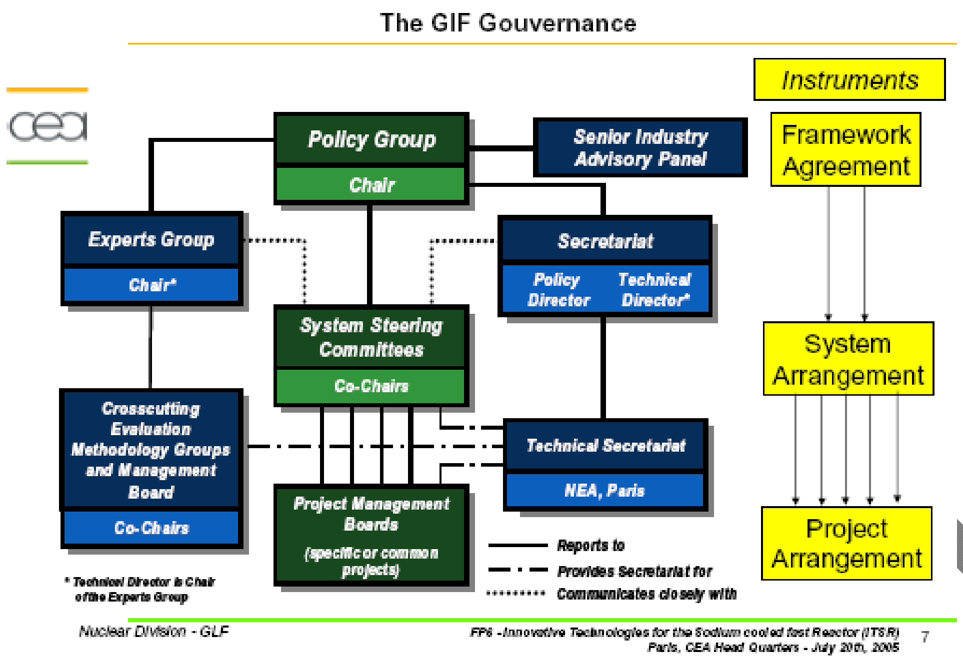

Figure 6. The GIF Governance structure

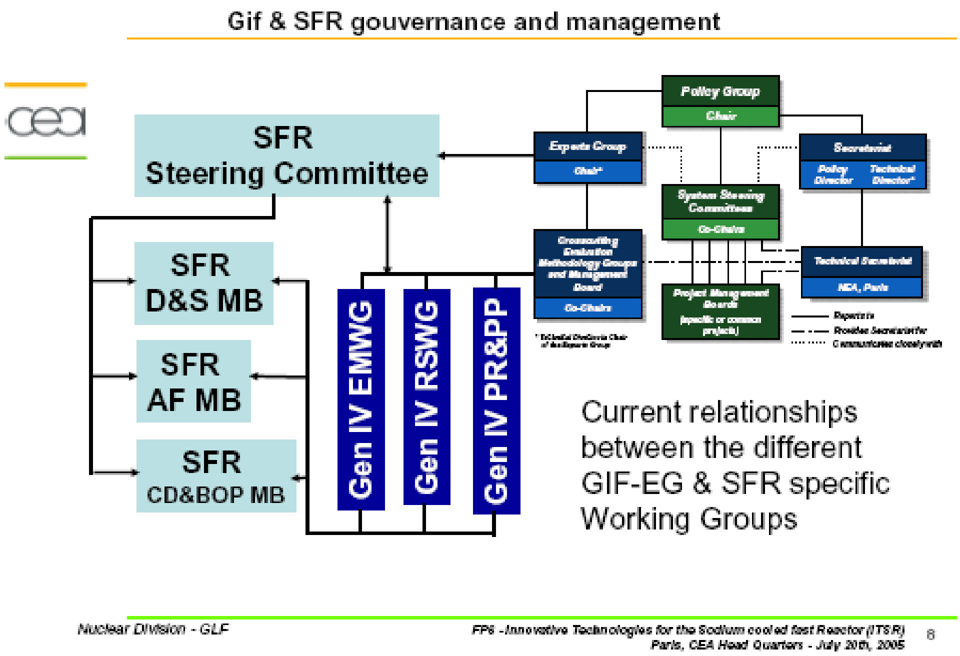

Figure 7. The SFR management structure & links with the GIF Governance

ITSR Management & links with the Gif / SFR

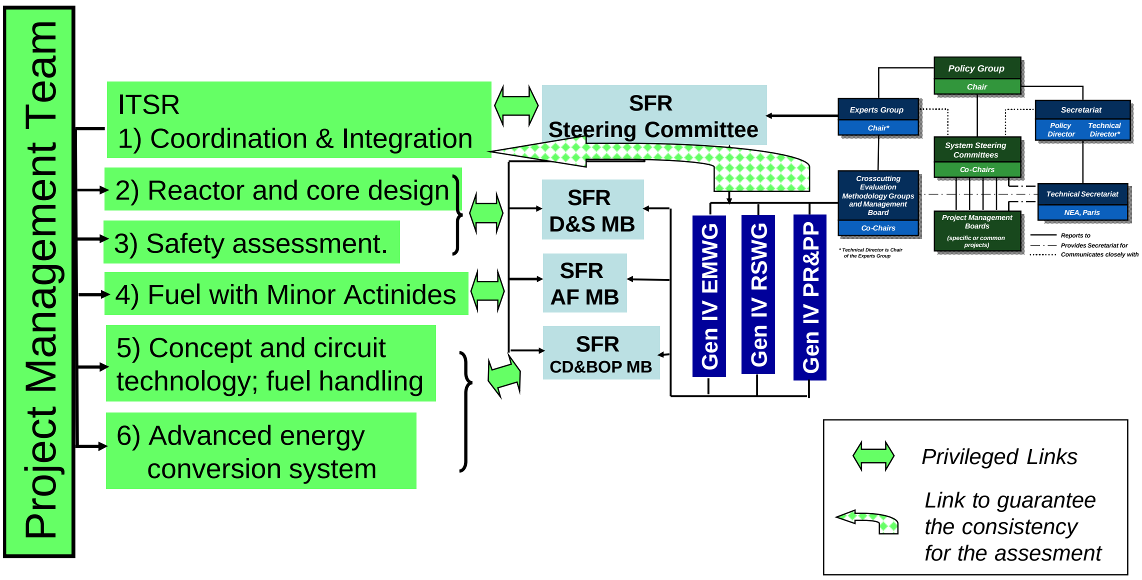

Figure 8. Links between the ITSR, the GenIV SFR Project & the GIF governance